Ref. Ares (2018)4843939 - 20/09/2018

Intelligent Fish feeding through Integration of ENabling technologies and Circular principles

Grant Agreement (GA) No: 818036

D4.8 Report on Environmental Life Cycle Assessment

Version: 2.0

Date: 21 – Aug - 2023

Document type:	Report
Dissemination level:	Public

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 818036

Project data

Project Title:	Intelligent Fish feeding through Integration of ENabling technologies and Circular principle
Project Grant Agreement (GA) No:	818036
Project Acronym:	iFishIENCi
Duration:	57 months, 1 November 2018 – 31 July 2023
Type of action:	Innovation Action

Deliverable Administration and Summary

Status:	Final	Due:	M57	Date:	31-Jul-23
Author (s)	Steven Prescott (ABT)				
Reviewer	Freya Robinson (ABT)				
WP	4	Deliverable Nr.	4.8	Relative Nr.	25
Comments					

Document change history

Version	Date	Author	Description
1	21-Aug-23	Steven Prescott	LCA
2	01-Nov-23	Freya Robinson	Review

Suggested reference to this deliverable: Deliverable number, Deliverable title (Year of publication), Intelligent Fish feeding through Integration of ENabling technologies and Circular principle (iFishIENCi) Horizon 2020 project under Grant Agreement (GA) No: 818036

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 818036

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1 Introduction

1.1 Background and introduction to this document

1.2 A basic introduction to Life Cycle Assessment

Life Cycle Assessment is a useful methodology for exploring the sustainability of economic products and services. The value-chain of any given product is associated with the use of material resources and with emissions to air, water, and land, all of which can contribute to a variety of environmental impacts. In LCA, these inputs and emissions are detailed within an inventory for each stage of the value-chain. Their contribution towards a selection of environmental impact categories is then calculated using environmental impact models. Environmental impacts occur at various scales ranging from localised to global. An example of local-scale impacts is the benthic nutrient enrichment which sometimes occurs beneath fish-farms. A good example of a global-scale impact is global warming. Typically, life cycle assessment does not include local-scale impacts, instead it focuses upon wide-scale impacts, such as those occurring at a global level. The impact models commonly used in LCA calculate potential environmental impacts. In other words, they calculate the impacts that may, but not definitely, occur. A key reason for this is that some emissions have the potential to contribute to a variety of impacts, but there is no certainty as to which impacts the emission will contribute, or as to how much it will contribute to each. This can be expected to vary over time and according to multiple factors. As such, emissions are not allocated between impacts according to their actual, or estimated contribution (e.g., 15% of emission X contributes to impact A, 20% to impact B, and 65% to impact C). When an emission has the potential to contribute to a variety of impacts, they are double (or triple, or quadruple etc.) counted, so that the full quantity of that emission is treated as contributing to each of the impacts individually (e.g., 100% of emission X contributes to impact A, 100% to impact B, and 100%). Task 4.4. Life Cycle Assessment: Goal and Scope iFishIENCi - 818036 20/3 Life Cycle Assessments calculate the potential environmental impacts of product functions. The concept of product function is not only important for understanding LCA, but also for understanding product sustainability as a concept. Products are purchased because of the function they provide. A consumer does not obtain a lightbulb for the sake of mere possession. A lightbulb is obtained because it produces light. Furthermore, a range of lightbulbs are available, producing different qualities of light and for a variable amount of time. The function of a 60W incandescent lightbulb might be the provision of 800 lumens (lm) of light for a period of 1000 hours. A consumer may have a dark, windowless book room for which light is required to allow reading. A light bulb emitting 800lm of light may be ideal for this purpose. Two alternative 60w light bulbs may be available for purchase: light bulb A produces 800lm; light bulb B emits only 400. The logical choice for the consumer is to purchase option A, as this provides the desired function. The two light bulbs are not functionally equivalent. One enables the consumer to read, the other does not. Light bulb B may have a functional lifetime that is half that of A. Instead of producing 800lm for 1000 hours, it emits 400lms for 500. An LCA comparing the life cycle impacts of light bulb A and light bulb B would yield limited information because in the real world, they are not directly substitutable; 1 light bulb B is insufficient to produce enough light to make reading possible. It would be much more suitable to perform an LCA comparing the two products upon the basis on an equivalent unit of function. In this case, the functional unit could be quantified as 1000 hours of 800lm. To fulfil this function the consumer can obtain either 1 light bulb with option A, or 4 lightbulbs with option B (using option B you need 2 light bulbs to deliver 800lm for 500 hours, and another 2 to emit 800lm for the next 500 hours). Thus, an LCA comparing the two product options based upon a functional unit of 1000 hours of 800lm will be a comparison between 1 option A lightbulb and 4 option B lightbulbs. In LCA terminology, the required quantity of lightbulbs to fulfil the functional unit is the reference flow.

1.3 Application of LCA to fish aquaculture

Life cycle assessment has been applied to several species of finfish produced in different cultivation systems. These studies show that the provision of feed (production of feed and feed ingredients) and energy use (e.g., electricity provision) can, in many cases, be expected to be key contributors towards environmental impacts. However, the inclusion of infrastructure within the assessment has often been neglected. This is largely due to the difficulty of obtaining data and constructing inventories of equipment and construction material. Those studies in which infrastructure was assessed, suggest that infrastructure may make significant contributions. In most cases, the assessments are of inventories that are complete, with only generic materials being included, and without the conversion of these materials into items of infrastructure or equipment. Depending on the goal of the study, this isn’t necessarily a problem. However, in the present situation, life cycle inventories of cultivation infrastructure are mostly either absent or otherwise lacking in representativity. Improvements to the completeness and representativeness of aquaculture life cycle inventories should lead to greater confidence in the results of LCA. Infrastructure appears to be a case in point. This is of direct relevance to the iFishIENCi project; the intended LCA features several cultivation systems between which a major difference is the infrastructure employed.

Ideally, and as according to ISO 14040/14044 (2006), product Life Cycle Assessments should cover the entire value chain. A value chain begins at the point at which required materials are extracted from the natural environment. Such activities include the mining of coal, which is used to produce electricity. They also include the mining of metals, which are subject to further economic transformation, eventually becoming components of machinery, transport, or other infrastructure used at various stages along the value chain. The value chain contains all economic processes required to fulfil the functional unit (see section 4.2). A full value chain includes a product use phase (the use of a product by a consumer), followed by a disposal phase and *end-of-life* phase that includes the processes by which the product is either recycled or broken-down (e.g., decomposition of 'organic' materials) into its constituent compounds and elements that re-enter the 'natural' ecosystem. However, it is common for the assessment to terminate at a phase occurring before, or *upstream* of, the disposal and consumer use phases. Life Cycle Assessments of food and aquaculture products are certainly no exception, with many assessments ending at, or immediately after, the point of harvest: the ***farm-gate***.

1.4 Basic goal and scope

The original goal and possible scope were outlined in Deliverable 4.6 (entitled 'Scope and system boundaries for environmental Life Cycle Assessment'). This deliverable describes the various research areas and scenarios presented by the iFishIENCi project for which LCA might be suitable for analysing their sustainability. As is commonly inherent to the LCA process, the goal has been revisited and revised according to considerations such as the availability of data and other resources. **At the final revision, a scenario based upon the production of catfish in RAS, and the circular, 'Waste2Value concept', was chosen as the subject for assessment.**

The 'Waste2Value' value chain was separated into 4 main product stages (the inventory structure is described below), these being:

PS. 1) Aquafeed production.

PS.2) Catfish growout in RAS.

PS.3) Nutrient extraction from sludge.

PS.4) Algae meal (*Nannochloropsis gaditana*) production.

Aquafeed has been further separated into two sub-stages with reference flows and functions that can be considered similar, allowing the substages to be compared:

PS1.a) Standard diet.

PS1.b) Algae meal containing diet.

Algae production has also been separated into two sub-stages with reference flows and functions that can be considered similar, allowing the substages to be compared:

PS.4.a) *Nannochloropsis gaditana* produced using a conventional nutrient mix to support primary productivity.

PS.4.b) *Nannochloropsis gaditana* produced using nitrogen extracted from sludge to support primary productivity.

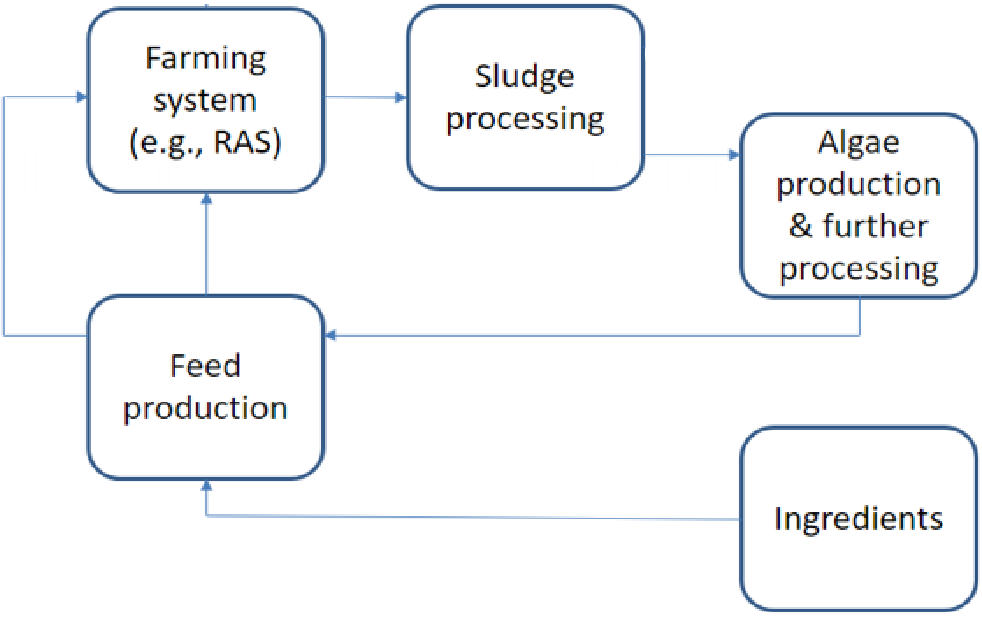


Figure 1. Diagram displaying the circularity of economic flows (blue arrows) and the basis of the Waste2Value value chain concept. The production of ingredients (other than algae) is a major stage of the value chain but it not inherently part of the circular flow.

Thus, the assessment of catfish production ends at the farm-gate, whereas the assessment of sludge as an economic flow continues past this point but can also become an upstream input to the catfish value chain as a substrate for the production of algal biomass.

1.5 Life Cycle Inventory structure

Each product stage is separated into system processes. System processes may be further delineated into system sub-processes (SSP). All system processes (and any sub-processes) contain unit processes (UPR), which were usually items of equipment/infrastructure. A common approach was adopted towards the creation of unit process inventories. Information describing major material inputs to these unit processes was selected from commercial product brochures and from AquaBioTech brand items of equipment. When possible, data describing energy consumption was collected for individual unit processes. All infrastructure (items of equipment) were assumed to have travelled the same distance (from the point product production to delivery at the product stage where they are used, e.g., point of manufacture of water pump, to arrival of pump at the RAS facility) by road, rail, and airfreight, considered suitable for a European context (Table 1). These distances are expressed as tonne or kilogram kilometres (tkm or kgkm), a metric calculated as the mass multiplied by the distance travelled. Ecoinvent processes were used to describe the mode of transport, these being '*Transport, freight, lorry, unspecified {GLO}| market group'* (for road), '*Transport, freight train {GLO}| market group*' (for rail), and '*Transport, freight, aircraft, short haul {GLO} market*' (for airfreight).

Table 1. The assumed distanced travelled by each transport modality.

Transport mix	**km**
Road	787.5
Rail	46.3
Air	38.4
Total	872.2

2 Catfish feed

Feed production is a major contributor to the environmental impacts of intensive aquaculture production (Pelletier et al. 2009; Roberts et al. 2015; Bohnes et al. 2018). The agricultural production of terrestrial crops accounts for much of the environmental burden carried by feed production, but other feed ingredients are also important. The inventory for catfish feed was based on formulas provided by MATE (Table 2), one formula for a reference (considered representative of a conventional) diet, and the other formula in which *Nannochloropsis gaditana* meal was included at a rate of 5%. The performance of both these formulas was tested in breeding experiments, as described in deliverable. The processes included in the inventories of these diets are shown in Table 3 and Table 4. The processes used were from the ecoinvent databases and the Agri-footprint database. However, there was no process for hydrolysed poultry protein and so this was modelled according to data presented by Ramirez-Mosquera (2012). This consisted of two system processes, one for the production of processed animal (poultry) protein, rendered poultry fat, and hydrolysed feather protein (Table 4) and another for the production of unprocessed poultry products from slaughtering (Table 5).

Unfortunately, no data describing the commercial manufacture of feed was made available through the project. Thus, data describing energy consumption per 1kg of feed was assumed to be the same as reported by Pelletier et al. (2009) for salmonid diets. Similarly, data describing infrastructure was also unavailable, and so infrastructure was not included in the assessment.

Table 2. Ingredient inclusion rate for the standard diet and (algae meal containing diet).

Ingredient	**Standard**	**Diet incl. algal meal**
	Inclusion rate (%)	**Inclusion rate (%)**

Nannochloropsis meal	0	5
Wheat meal	17.5	17.5
Soyabean meal (46%)	24	22
Extruded soyabean meal	8	5
Wheat gluten (70%)	10	10
Corn gluten (60%)	10	10
Provisoy	10	10
Hydrolysed poultry protein	6	6
Fish meal (60% protein)	6	6
Animal fat	4	4
Fish oil	3	3
Cargil catfish premix (1.5%)	1.5	1.5

Table 3. Inventory of inputs of outputs (and their quantities) for the standard diet. The table shows which processes have been used to represent these inputs and outputs, which have been, apart from hydrolysed feather meal, selected from the ecoinvent and Agri-footprint database.

Product	**Value**	**Unit**
Clarias gariepinus feed, extruded, production {HU}	1	kg
Ingredients	**Value**	**Unit**
Wheat middlings & feed, at processing/HU Economic	0.175	kg
Soybean meal {BR}| soybean meal and crude oil production | APOS, U	0.24	kg
Soybean, feed {GLO}| market for | APOS, U	0.08	kg
Wheat gluten feed, at processing/DE Economic	0.1	kg
Maize gluten feed dried, at processing/DE Economic	0.1	kg
Soybean protein-concentrate, at processing/BR Economic	0.1	kg
Fat from animals, at processing/NL Economic	0.04	kg
Hydrolysed feather meal	0.06	kg
Fish oil, from anchovy {GLO}| market for fish oil | APOS, U	0.03	kg
Fishmeal, 63-65% protein {GLO}| market for fishmeal, 63-65% protein | APOS, U	0.06	kg
Electricity/heat	**Value**	**Unit**
Electricity, medium voltage {HU}| market for | APOS, U	0.4699	kWh
Heat, district or industrial, natural gas {RER}| market group for | APOS, U	0.1243	MJ
Heat, {Europe without Switzerland}|light fuel oil, at boiler 10kW, non-modulating | APOS, U	0.0528	MJ
Heat, from steam, {RER}| market for | APOS, U	0.1766	MJ

Table 4. Inventory of inputs of outputs (and their quantities) for the production of valorised poultry byproducts.

Products	**Value**	**Unit**	**Allocation (economic)**
Poultry processed animal protein	0.163	kg	32.2761 %
Poultry rendered fat	0.101	kg	21.9239 %
Hydrolysed feather meal	0.067	kg	45.8 %

Input products			
Chicken offal and bone (cat 3)	1	kg	
Chicken feathers (cat 3)	0.265	kg	
Tap water {Europe without Switzerland} | market for | APOS, U	0.525	kg	
Sodium hypochlorite, without water, 15% solution state {RER}| market for| APOS, U	0.00134	kg	
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	0.000777	kg	
Sulfuric acid {RER}| market for sulfuric acid | APOS, U	0.000369	kg	
Electricity/heat inputs			
Electricity, medium voltage {RER}| market group for | APOS, U	224.3	kJ	
Heat, central or small-scale, natural gas {RER}| market group for | APOS, U	2886.1	kJ	

Table 5. Inventory of inputs of outputs (and their quantities) for the production of poultry byproducts (from slaughtering). Input and output processes have been selected from the ecoinvent 3 database. The quantities of inputs, outputs, and byproducts, and values for byproduct allocation, where obtained from Ramirez-Mosquera (2012).

Products	**Value**	**Unit**	**Allocation (economic)**	
Whole chicken (eviscerated)	0.033	kg	3.59	%
Chicken quarters and halves	0.001	kg	0.2	%
Chicken Wings	0.062	kg	4.26	%
Chicken Fillets	0.209	kg	69.91	%
Chicken Legs	0.197	kg	18.82	%
Chicken Trims	0.008	kg	0.41	%
Chicken Edible offal	0.042	kg	0.53	%
Chicken offal and bone (cat 3)	0.329	kg	2.26	%
Chicken feathers (cat 3)	0.064	kg	0.02	%
Materials/fuels	**Value**	**Unit**		
Chicken for slaughtering, live weight {GLO}| market for | APOS, U	1	kg		
Tap water {RER}| market group for | APOS, U	2.439	kg		
Electricity/heat	**Value**	**Unit**		
Electricity, medium voltage {RER}| market group for | APOS, U	0.379	MJ		
Heat, central or small-scale, {RoW}|light fuel oil, at boiler 10kW, non-modulating | APOS, U	0.1542	MJ		
Emissions to air	**Value**	**Unit**		
Methane, chlorodifluoro-, HCFC-22	0.00001555	kg		
Waste products	**Value**	**Unit**		
Wastewater, average {Europe without Switzerland} | market for wastewater, | APOS, U	0.002	m3		

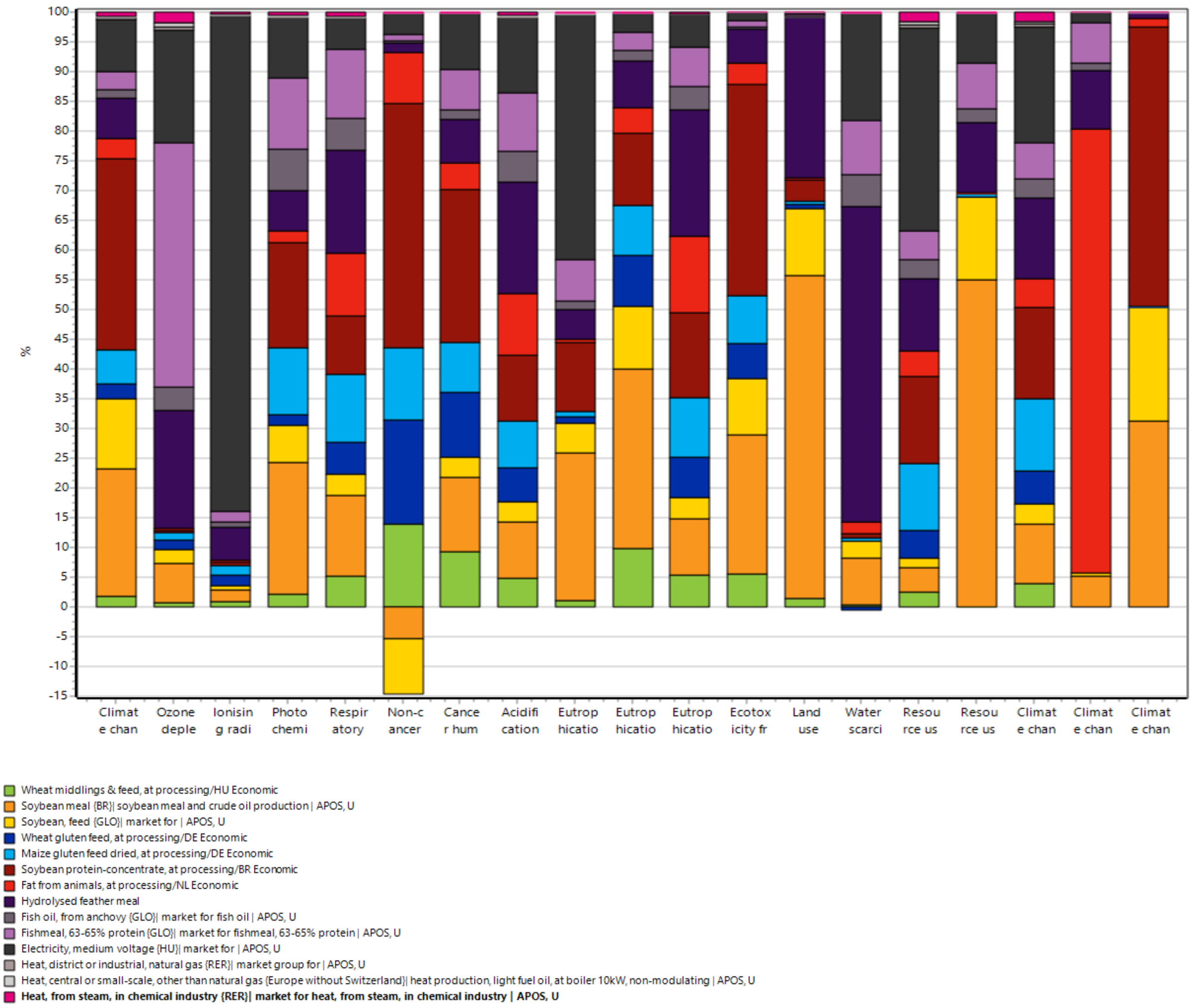


Figure 2. Characterised potential environmental impacts from the production of the standard diet. Assessed using the Environmental Footprint assessment 2.0. method.

3 Catfish growout in RAS

3.1 System description and Life Cycle Inventory

A hypothetical RAS facility was designed to accommodate the production of 1000 tonne live-weight of African catfish per year, with a harvest weight of 500g per individual fish. A biomass production plan based upon an established growth curve (Figure 3) was made to achieve this production through 17 complete cycles per year, allowing frequent harvesting and a regular supply to market.

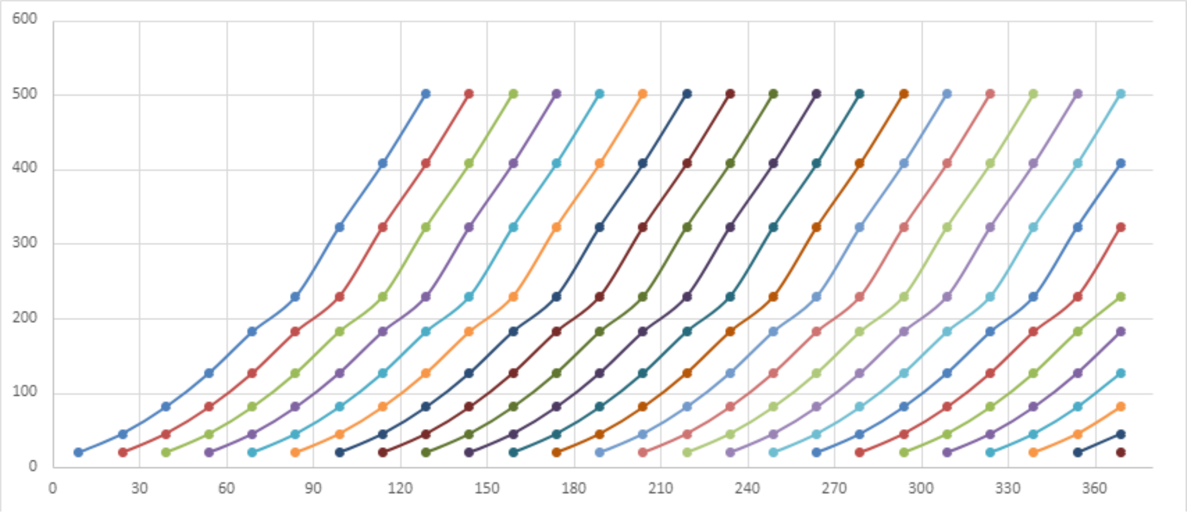


Figure 3. Chart depicting the growth curve, stocking and harvesting schedule of each separate cohort (batch) of African catfish, within the space of a year. The horizontal axis represents time in days, the vertical axis represents mass per individual, expressed in grams.

The biomass plan was combined with a nutrient mass balance model to predict the quantity of solid bound and dissolved nutrients released through the feeding of fish and subsequent metabolic activity (Figure 4). It was also combined with oxygen and carbon dioxide mass balance calculations, as well as calculations for estimating the water flowrate.

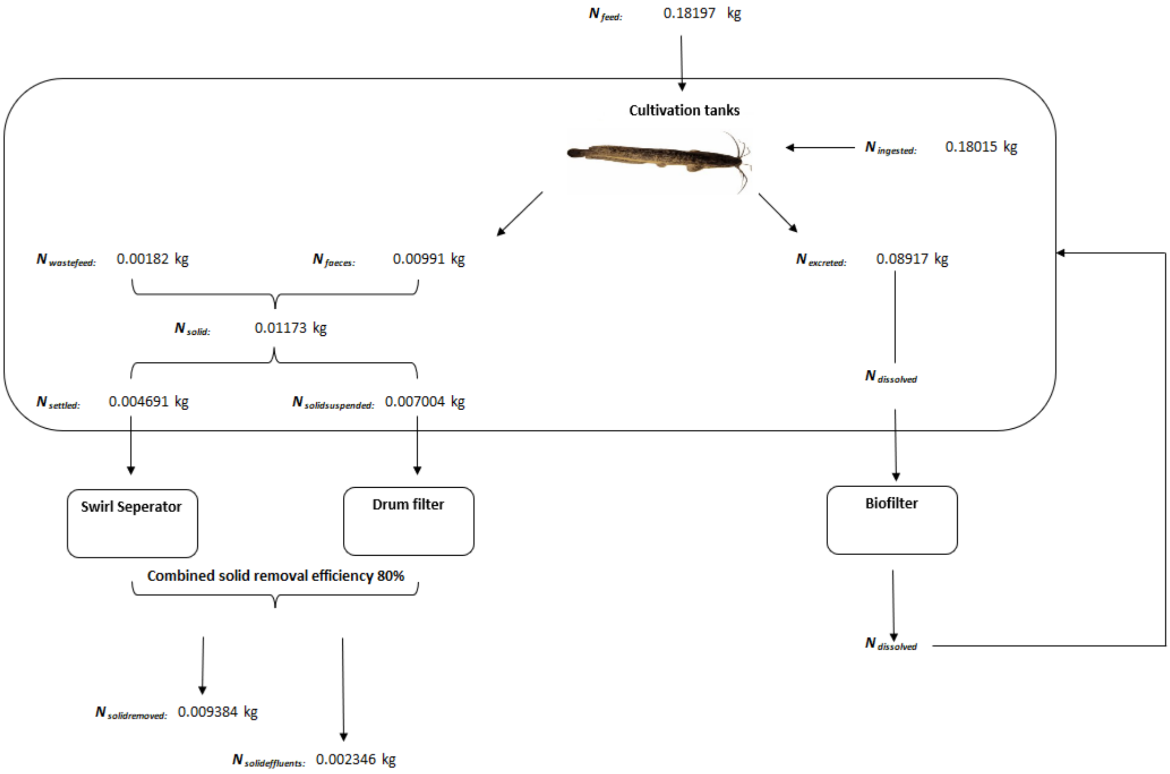


Figure 4. Diagram representing the nitrogen mass balance model for RAS production of catfish. The flow quantities were used to calculate the quantity of total nitrogen emitted the environment. They were also used to inform the selection of various items of equipment (such as the type and size of drum filters, biofilters etc).

The resulting information allowed the determination of the required number and size of cultivation tanks, drum filters, biofilters, infrastructure required for sludge treatment, and other items of equipment, which were all compiled into a bill-of-quantities. The system was separated into for system processes, these being SP.1) water abstraction and filtration, SP.2) cultivation, SP.3) sludge management, and SP.4) harvesting. Cultivation was itself further separated into two sub processes, each being the separate loop one circulating water. Subprocesses a is the main cultivation loop and subprocesses b is for protein skimming and ozonation of water from the biofilter.

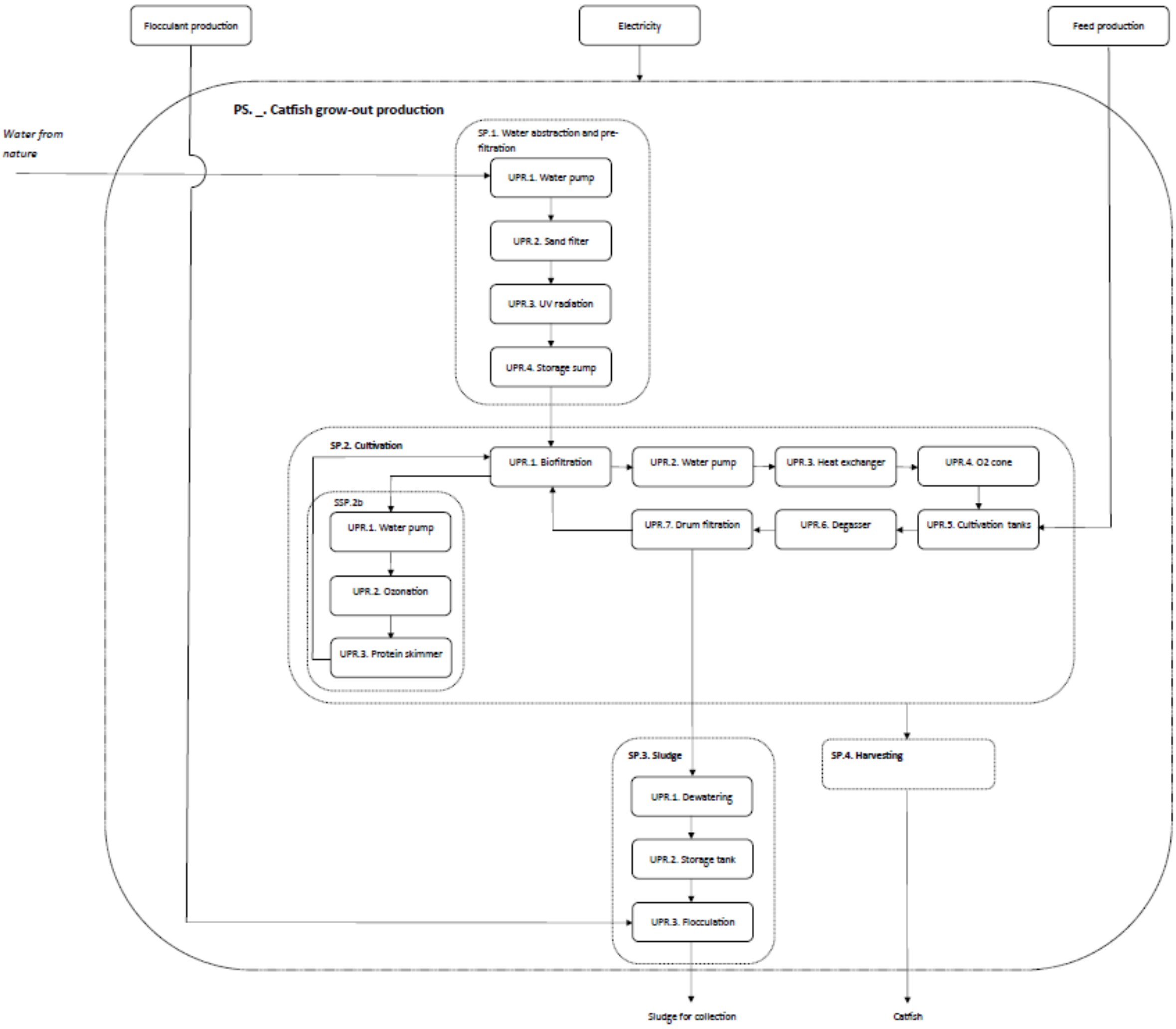
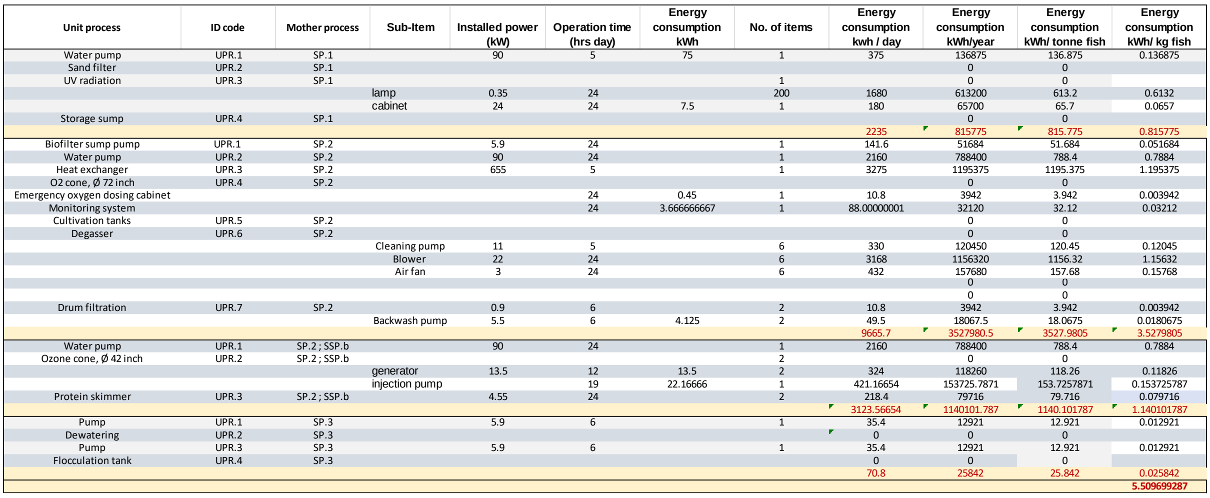


Figure 5. Flow diagram depicting the material flows (arrows) connecting the system processes (SPR) and unit processes (UPR) therein, of the catfish RAS growout product-stage.

Information relating to the power consumption of energy drawing equipment was also collected and used to calculate the power consumption of the RAS and per unit mass of fish (Table 6).

Table 6. Energy rating and use data per item of RAS equipment and per unit mass of fish



Unit process	ID code	Mother process	Sub-Item	Installed power (kW)	Operation time (hrs day)	Energy consumption kWh	No. of items	Energy consumption kwh / day	Energy consumption kWh/year	Energy consumption kWh/ tonne fish	Energy consumption kWh/ kg fish
Water pump	UPR.1	SP.1		90	5	75	1	375	136875	136.875	0.136875
Sand filter	UPR.2	SP.1							0	0	
UV radiation	UPR.3	SP.1					1		0	0	
			lamp	0.35	24		200	1680	613200	613.2	0.6132
			cabinet	24	24	7.5	1	180	65700	65.7	0.0657
Storage sump	UPR.4	SP.1							0	0	
								2235	815775	815.775	0.815775
Biofilter sump pump	UPR.1	SP.2		5.9	24		1	141.6	51684	51.684	0.051684
Water pump	UPR.2	SP.2		90	24		1	2160	788400	788.4	0.7884
Heat exchanger	UPR.3	SP.2		655	5		1	3275	1195375	1195.375	1.195375
O2 cone, Ø 72 inch	UPR.4	SP.2							0	0	
Emergency oxygen dosing cabinet					24	0.45	1	10.8	3942	3.942	0.003942
Monitoring system					24	3.666666667	1	88.00000001	32120	32.12	0.03212
Cultivation tanks	UPR.5	SP.2							0	0	
Degasser	UPR.6	SP.2							0	0	
			Cleaning pump	11	5		6	330	120450	120.45	0.12045
			Blower	22	24		6	3168	1156320	1156.32	1.15632
			Air fan	3	24		6	432	157680	157.68	0.15768
									0	0	
									0	0	
Drum filtration	UPR.7	SP.2		0.9	6		2	10.8	3942	3.942	0.003942
			Backwash pump	5.5	6	4.125	2	49.5	18067.5	18.0675	0.0180675
								9665.7	3527980.5	3527.9805	3.5279805
Water pump	UPR.1	SP.2 ; SSP.b		90	24		1	2160	788400	788.4	0.7884
Ozone cone, Ø 42 inch	UPR.2	SP.2 ; SSP.b					2		0	0	
			generator	13.5	12	13.5	2	324	118260	118.26	0.11826
			injection pump		19	22.16666	1	421.16654	153725.7871	153.7257871	0.153725787
Protein skimmer	UPR.3	SP.2 ; SSP.b		4.55	24		2	218.4	79716	79.716	0.079716
								3123.56654	1140101.787	1140.101787	1.140101787
Pump	UPR.1	SP.3		5.9	6		1	35.4	12921	12.921	0.012921
Dewatering	UPR.2	SP.3						0	0	0	
Pump	UPR.3	SP.3		5.9	6		1	35.4	12921	12.921	0.012921
Flocculation tank	UPR.4	SP.3						0	0	0	
								70.8	25842	25.842	0.025842
											5.509699287

Table 7. Items of RAS equipment, their quantity, and their life-span adjusted mass allocated per unit mass of catfish produced.

Item	No. of items	Lifespan	kgYrs / kg determining product
Pump (with motor) 4000 m3/hr {RER}, market for	1	5	0.0000002
Sand filter, {RER} market for	1	6	1.66667E-07
UV disinfection reactor and control cabinet, {RER} market for	10	5	0.000002
Storage sump, {RER} market for	1	10	0.0000001
Biofilter sump, 500 m3 {RER}, market for	1	10	0.0000001
Pump (with motor) 4000 m3/hr {RER}, market for	1	5	0.0000002
Heat exchanger {RER}, market for	1	5	0.0000002
O2 cone, Ø72 inch {RER}, market for	7	10	0.0000007
Circular tanks 150 m3 GRP {RER} market for	10	10	0.000001
Degasser tower, 1200 m3/hr {RER}, market for	6	10	0.0000006
Drum filter, capacity 3240m3/hr {RER}, market for	2	6	3.33333E-07
Pump (with motor) 4000 m3/hr {RER}, market for	1	5	0.0000002
Ozone cone, Ø42 inch {RER}, market for	2	10	0.0000002
Protein skimmer {RER}, market for	2	10	0.0000002
Centrifugal pump (incl. motor) 5.5 kW {RER}, market for	1	5	0.0000002
Gravimetric sludge dewatering cone {RER} market for	3	10	0.0000003
Centrifugal pump (incl. motor) 5.5 kW {RER}, market for	1	5	0.0000002
Sedimentation flocculation tank {RER} market for	1	10	0.0000001

Figure 6 shows the characterised impact assessment for three different types of inputs to African catfish produced in RAS: water supply, aquafeed, infrastructure, energy, and discharged water. As may be expected for RAS, feed and energy consumption are the dominant contributors towards most of the impact categories. Feed is the greatest single contributor towards 11 out of the 19 categories, and energy the greatest towards 5. Respectively, nutrient discharges account for 52.4% and 89% of the contributions towards freshwater eutrophication and marine eutrophication. The contribution of infrastructure is non-negligible and has a clear contribution towards many of the impacts, its greatest being towards mineral and metal resource use (16.9%). The overall dominant contribution of feed is normal for intensively fed aquaculture, and it is normal for energy use to feature prominently in LCAs of RAS (e.g., Song et al. 2019). Although infrastructure has lesser contributions, its inclusion in RAS LCA deserves further exploration, especially considering that promotion of RAS has spiked in recent years and energy use and capital inputs distinguishing features of this approach to cultivation.

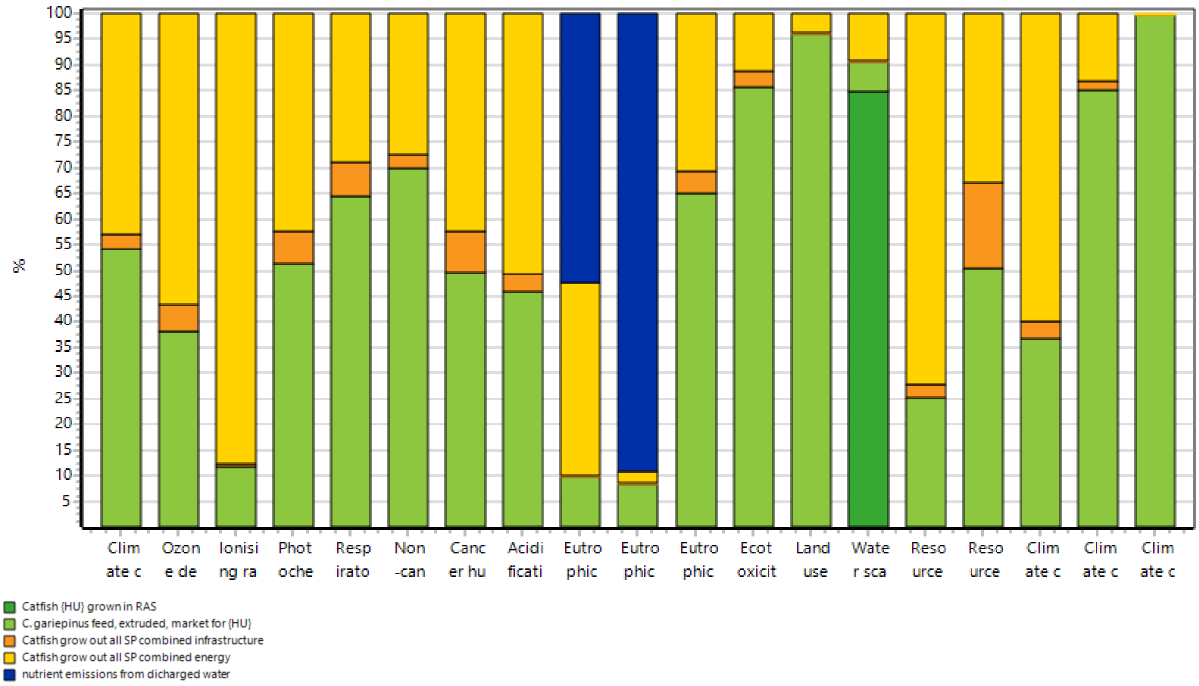


Figure 6. Characterised potential environmental impacts from the production for three different types of inputs to African catfish produced in RAS: water supply, aquafeed, infrastructure, energy, and discharged water. Assessed using the Environmental Footprint assessment 2.0. method.

Table 8. Contributions to impact categories of RAS catfish production expressed as category indicator units (e.g., kg CO_2 eq.).

Impact category	Unit	Total	Water supply	Feed	Infrastructure	Energy	Discharged water
Climate change	kg CO2 eq	6.129	0.000	3.322	0.169	2.639	0.000
Ozone depletion	kg CFC11 eq	0.000	0.000	0.000	0.000	0.000	0.000
Ionising radiation, HH	kBq U-235 eq	2.311	0.000	0.272	0.012	2.026	0.000
Photochemical ozone formation, HH	kg NMVOC eq	0.014	0.000	0.007	0.001	0.006	0.000
Respiratory inorganics	disease inc.	0.000	0.000	0.000	0.000	0.000	0.000
Non-cancer human health effects	CTUh	0.000	0.000	0.000	0.000	0.000	0.000
Cancer human health effects	CTUh	0.000	0.000	0.000	0.000	0.000	0.000
Acidification terrestrial and freshwater	mol H+ eq	0.028	0.000	0.013	0.001	0.014	0.000
Eutrophication freshwater	kg P eq	0.010	0.000	0.001	0.000	0.004	0.005
Eutrophication marine	kg N eq	0.113	0.000	0.009	0.000	0.003	0.101
Eutrophication terrestrial	mol N eq	0.071	0.000	0.046	0.003	0.022	0.000
Ecotoxicity freshwater	CTUe	10.588	0.000	9.066	0.353	1.169	0.000
Land use	Pt	1905.625	0.000	1827.214	5.293	73.118	0.000
Water scarcity	m3 depriv.	7.985	6.774	0.443	0.027	0.740	0.000
Resource use, energy carriers	MJ	90.249	0.000	22.767	2.368	65.114	0.000
Resource use, mineral and metals	kg Sb eq	0.000	0.000	0.000	0.000	0.000	0.000
Climate change - fossil	kg CO2 eq	4.415	0.000	1.613	0.168	2.634	0.000
Climate change - biogenic	kg CO2 eq	0.019	0.000	0.016	0.000	0.002	0.000
Climate change - land use and transform.	kg CO2 eq	1.696	0.000	1.693	0.000	0.003	0.000

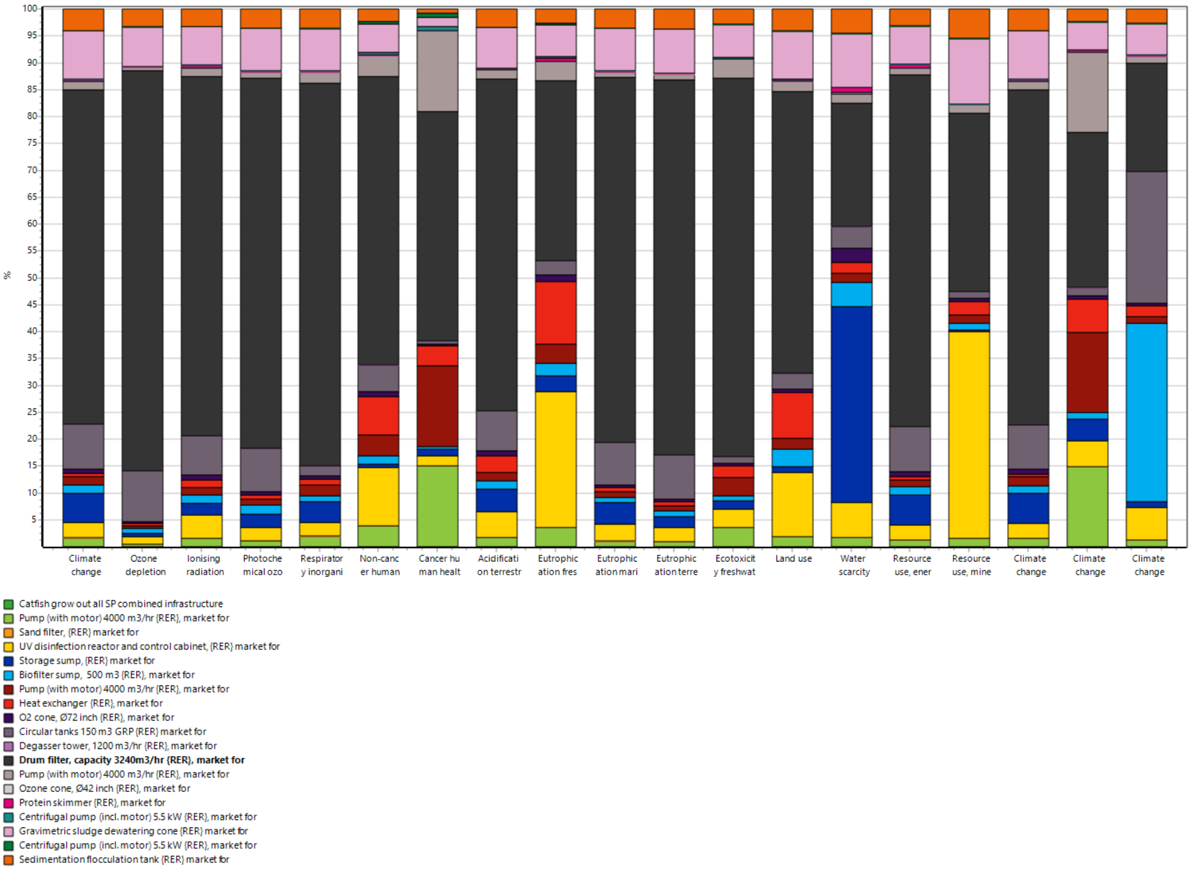


Figure 7. Characterised potential environmental impacts from the production and delivery of each item of RAS equipment for three different types of inputs to African catfish produced in RAS: water supply, aquafeed, infrastructure, energy, and discharged water. Assessed using the Environmental Footprint assessment 2.0. method.

Figure 6 and Table 8 represent an inventory in which the treated sludge (at the point of farm gate) is considered to be a burden free waste product, that is, all inputs and outputs are allocated to the production of fish and non to the sludge. Whether an economic flow is defined at a co-product, waste, or byproduct can have significant effects on the potential environmental impacts attributed to it. These definitions are given according to generally accepted criteria for good reasons and are not solely a matter of perception. In this study, sludge is considered a waste that will be valorised as method of waste management. However, if such a valorisation route was to become established, it is conceivable that sludge will be attributed a positive market value and thus become a byproduct that is exchanged in return for monetary payment. To explore how this may affect the sustainability of catfish produced in RAS and the consequent production of sludge, burdens were apportioned between the products according to mass-adjusted economic allocation. The economic value of sludge was determined according to the price of nitrogen (1.2 EUR/kgN) calculated from the yearly average price of ammonium nitrate fertiliser, and the value of catfish determined as its price at the farm-gate in Hungary (1.92 EUR/kg). This procedure allocates 99.27% of burdens to the production of catfish and only 0.73% to the production of sludge – hardly enough to be visible on the chart of characterised impacts, let alone make a significant difference. It can be surmised that given a scenario of large scale European wide catfish production in RAS, the valorisation of sludge and its subsequent use as a fertiliser (or perhaps nutrient supplement) as explored below, may be worthwhile and achieve environmentally beneficial outcomes, but it does little to alleviate the environmental impacts associated with RAS grown catfish per unit of production. This highlights the importance of how issues of sustainably are reported, and why thorough environmental analysis, including, but not limited to a life cycle/value chain approach, should be performed. This should facilitate a holistic understanding of the various dimensions of a products sustainability and help ensure that correct messages are communicated to consumers and policy makers, enabling sensible decisions that avoid the unintended consequences borne out of an incompletely represented context.

4 Sludge valorisation process

4.1 System description

Deliverable 1.6 describes the processes developed for the valorisation of sludge and water discharged from aquaculture. One of these, the treatment of sludge through ultrasonification and enzymatic hydrolysis, to produce a nitrogen ‘rich’ residue that was tested as a substrate for the production of microalgae, was chosen for inclusion within the LCA (Figure 8).

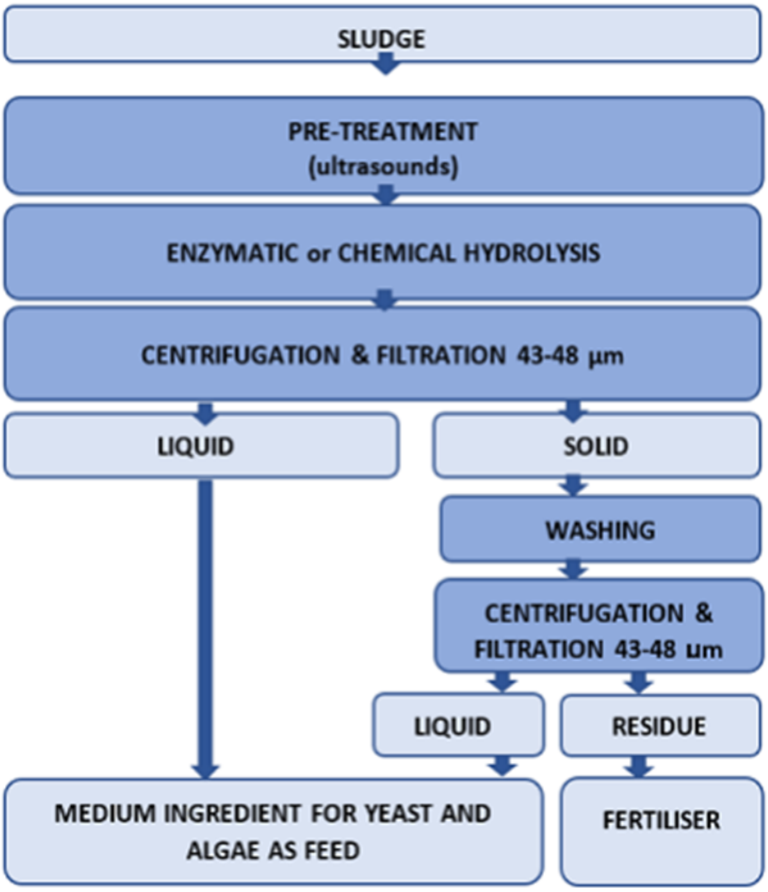


Figure 8. Flow diagram depicting the material flows (blue arrows) connecting the system processes that make up the nitrogen extraction (sludge valorisation) product stage (SP.1. sludge reception, SP.2. ultrasound pretreatment, SP.3. enzymatic hydrolysis, SP.4. enzymatic inactivation, SP.5. centrifugation, filtration, and washing).

Table 9. Inventory of inputs of outputs (unit processes) for each system process of the extraction of nitrogen from sludge product-stage. The unit process inventories have been compiled from secondary data sources as part of this study, other than for energy, water and enzyme inputs which were obtained from the ecoinvent database. The quantities of infrastructure items are adjusted according to the item lifespan and the calculated yearly production of nitrogen extracted from sludge.

System process:	**Sludge reception**	**Value**	**Unit**
Sludge (15.52% water cont.; 00303kgN/kg) market for		330.03	kg
System process:	**Ultrasound**	**Value**	**Unit**
Ultrasonic homogenizer, {RER} market for		0.0095683	Item
Water, deionised {Europe without Switzerland} | APOS, U		330.03	kg
Electricity, medium voltage {HU}| market for | APOS, U		152.32	kWh
System process:	**Enzymatic hydrolysis**	**Value**	**Unit**
Reactor vessel {RER}, market for		0.0095683	Item
Enzymes {GLO}| market for enzymes | APOS, U		0.97	kg
Enzymes {GLO}| market for enzymes | APOS, U		0.97	kg
Electricity, medium voltage {HU}| market for | APOS, U		287.38	kWh

System process:	**Enzymatic inactivation, sludge**	**Value**	**Unit**
Hot plate, {RER} market for		0.0095683	Item
Electricity, medium voltage {HU}| market for | APOS, U		34.53	kWh
System process:	**Centrifugation, filtration, and washing**	**Value**	**Unit**
Centrifuge {RER}, market for		0.0095683	Item
Overhead stirrer {RER}, market for		0.0095683	Item
Water, deionised {Europe without Switzerland} | APOS, U		330.03	kg
Filter {RER}, market for		406.19	p
Electricity, medium voltage {HU}| market for | APOS, U		591.62	kWh
Electricity, medium voltage {HU}| market for | APOS, U		5.08	kWh

Figure 10 shows the contributions of the three system processes towards characterised environmental impacts of nitrogen extracted from aquaculture sludge. The centrifugation, filtration, and washing process is the majority contributor to 15 of the 19 categories. It is exceeded by enzymatic hydrolysis in 3 other categories (climate change - land use and transformation, land use, and freshwater ecotoxicology). Its contributions towards land use are particularly significant (85.3% of total contributions to this impact category. Sludge reception and ultrasonification are the 3 largest contributors to all categories and in no case can their contributions be considered as approaching those of the other system processes in terms of quantity. However, their contributions are negligible. Contributions from the reception of sludge arise exclusively from transportation, as sludge is considered (in this LCA) to be an unintentional byproduct of RAS catfish production, and so no burdens are allocated to it. The generic European transport mix (Table 1) has been used to describe the transportation of sludge. It is clear that a reduction in the associated tonne kilometres is the only way to reduce environmental impacts in this scenario, but how this can be done in practice (reduced distance, choice of transportation modes) is less straight forward. The sludge reception and ultra sonification processes are followed by enzymatic inactivation, the contributions of which are clearly, proportionality insignificant. Being the two greatest contributors, the centrifugation, filtration and washing processes (SP.4) and the enzymatic hydrolysis process (SP.3), will be explored in more detail.

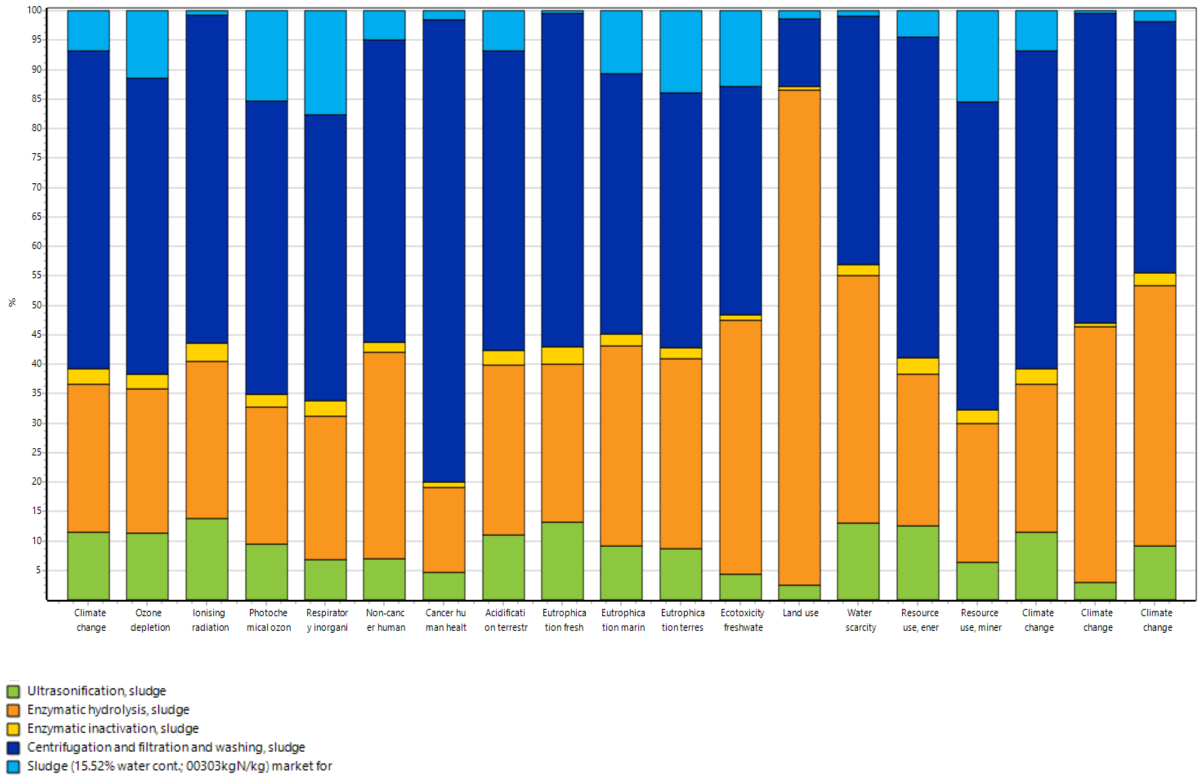


Figure 9. Characterised potential environmental impacts from each system process of the extraction of nitrogen from sludge product-stage. Assessed using the Environmental Footprint assessment 2.0. method.

The provision of electricity for the operation of the centrifuge is the dominant contributor of the centrifugation, filtration and washing process towards the impact categories (Figure 10.A). This is followed by contributions from the production of the centrifuge itself, principally the provision of steel and the processes required to work the steel into the form required for the assembly of the centrifuge (Figure 10.B). In the case of enzymatic hydrolysis (Figure 11) contributions from the provision of electrical energy and enzymes for hydrolysis overwhelmingly dominate all impact categories.

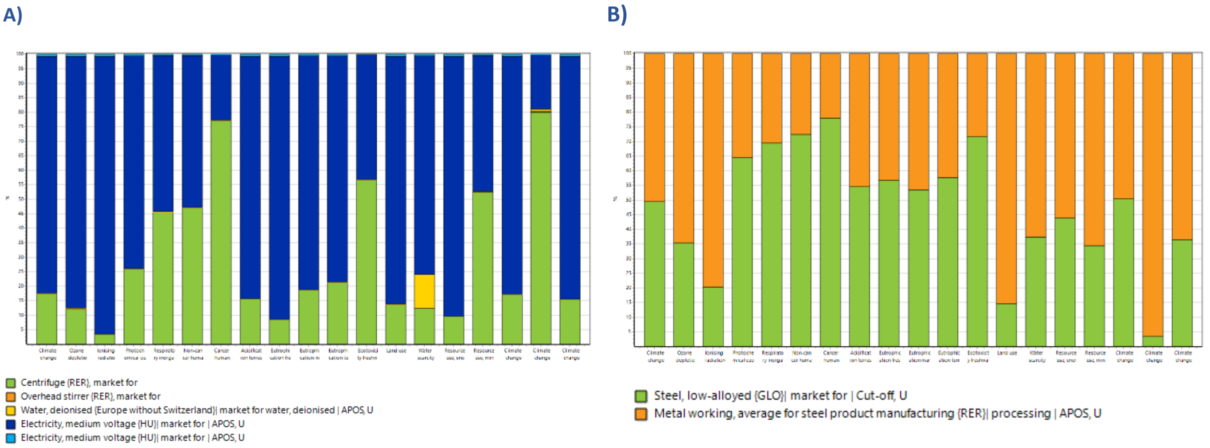


Figure 10. Characterised potential environmental impacts from **A)** the centrifugation, filtration and washing stage, and **B)** production of the centrifuge. Assessed using the Environmental Footprint assessment 2.0. method.

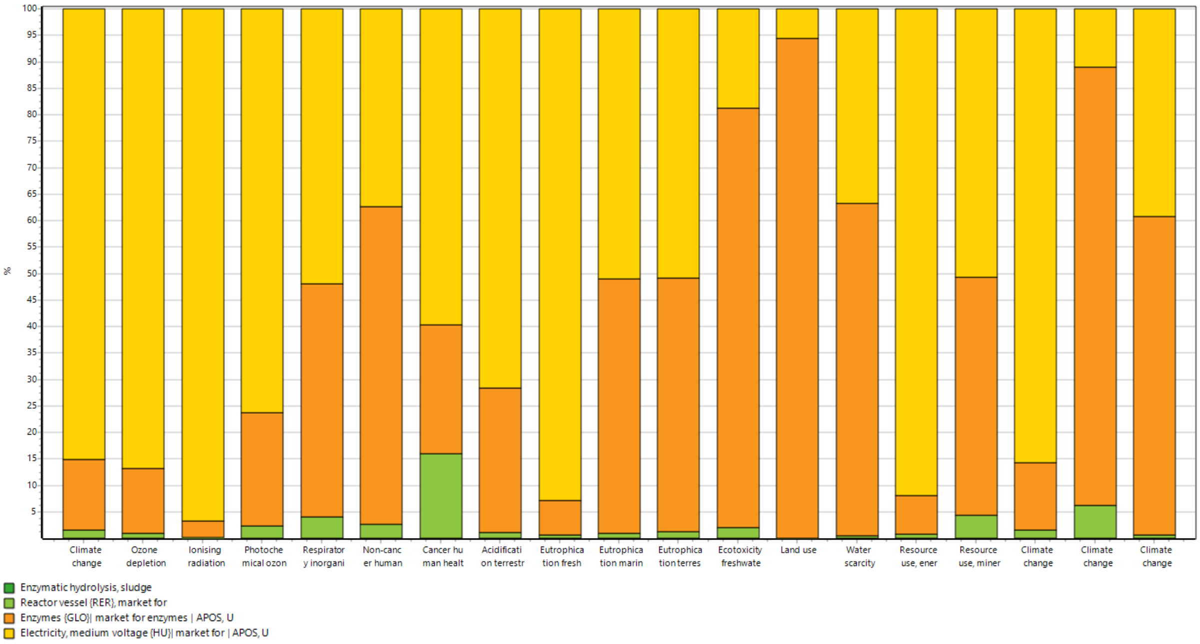


Figure 11. Characterised potential environmental impacts from the unit processes of the enzymatic hydrolysis system process (of the sludge valorisation product-stage). Assessed using the Environmental Footprint assessment 2.0. method.

5 *Nannochloropsis gaditana* meal production

The production of *Nannochloropsis gaditana* meal was assumed to take place in the Mongstag AlgaePARC (Norway), operated by NORCE. Inventory data was mostly acquired from the main publication and supplementary data presented by Vazquez-Romero et al. (2022). This was combined with further information from the NORCE, especially that describing the nutrient medium (Table 10). As is consistent with the aforementioned publication, the production stage was delineated into three (3) system processes, each consisting of their respective unit processes (Figure 12). The first stage, pre-cultivation, consists of the abstraction of water (assumed to be from a natural source), its filtration and irradiation, and the subsequent addition of the nutrient medium. The quantity of nutrient medium added was calculated according to its nitrogen content, with the required amount of nitrogen determined to be 0.09kg per kg of final product. Cultivation, the second stage, consists of two sub-system processes, one containing to the cultivation photobioreactors and water circulation, the other being for the provision of light and the correct temperature. The final stage, harvesting, contains those processes for concentrating and drying the harvested biomass to produce an algal meal with a 5% moisture content.

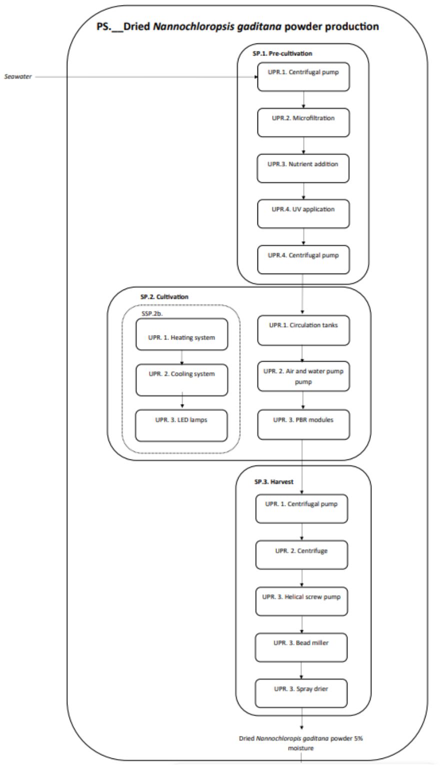


Figure 12. Flow diagram depicting the material flows (arrows) connecting the system processes (SPR) and unit processes (UPR) therein, of the *Nannochloropsis gaditana* dried meal product-stage.

Table 10. Quantity of constituent macronutrient and micronutrients of the standard nutrient mix used for the production of algal biomass.

Macronutrients	**mmol/L**	**mol/L**	**g/L**
Nitrate (NaNO3)	12.47	0.01247	1.05988
Phosphate (KH2PO4)	0.88	0.00088	0.11975
Trace mineral mix	**mmol/L**	**mol/L**	**g/L**
Boron (B)	0.031	3.1E-05	0.00033
Copper (Cu)	0.002	2E-06	0.00013
Iron (Fe)	0.043	4.3E-05	0.0024
Magnesium (Mn)	0.017	1.7E-05	0.00093
Molybdenum (Mo)	0.001	1E-06	9.6E-05
Zinc (Zn)	0.008	8E-06	0.00052

Alternatively, nitrogen extracted from the sludge valorisation processes was included in the inventory as a total replacement to the nutrient medium. As with the nutrient medium, the rate of its inclusion was according to a requirement of 0.09kg per kg of final product.

Figure 13 shows the characterised environmental impacts of *N. gaditana* dried meal production. Interestingly, provision of the nutrient medium features significantly, being the major contributor towards 11 out of the 19 impact categories. Energy consumption has commonly been found to be a major contributor towards the impacts of microalgae production, and the results displayed in Figure 13 are consistent with this expectable outcome. Infrastructure is not always included in LCAs of microalgae, but the results here show the importance of including items of equipment and building materials, and their combined contribution is not insignificant. Thus, one wishing to reduce the environmental impacts of the production of dried *N. gaditana* meal would do well to focus on each of the aforementioned inputs.

Crucially for the iFishIENCi, **the often-dominant contribution of nutrient provision towards these impacts supports the initiative to find a source associated with lower potential environmental consequences**.

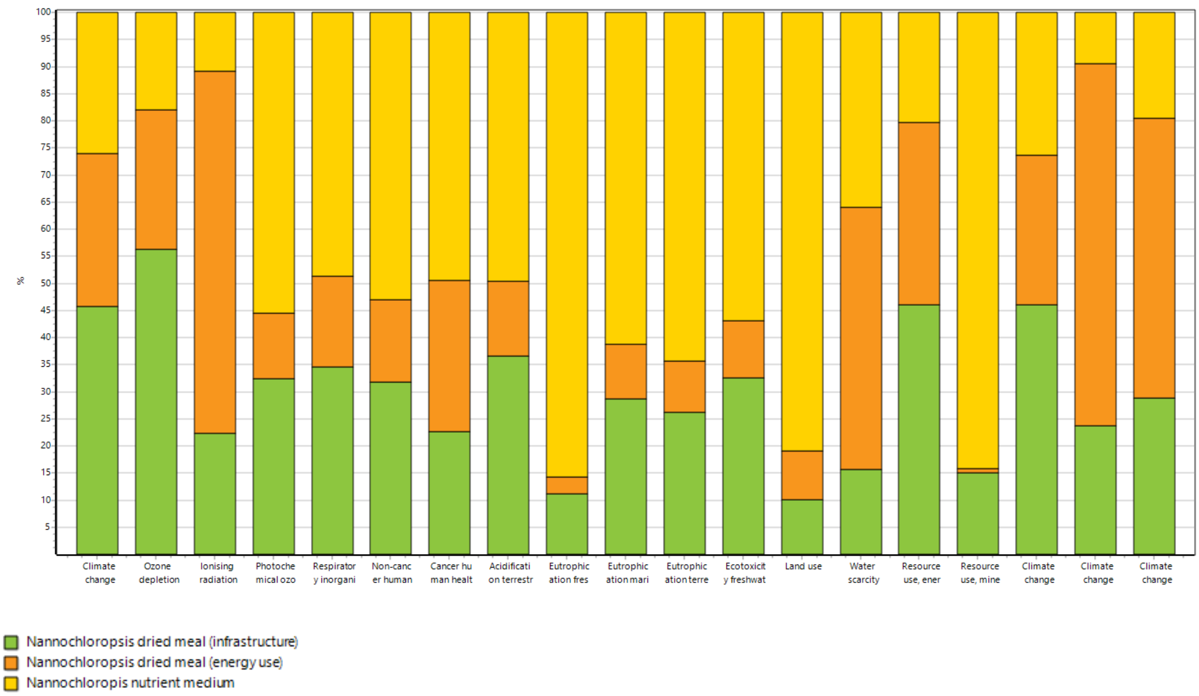


Figure 13. Characterised potential environmental impacts from infrastructure inputs, energy use, and supply of the nutrient medium, to the production of dried *Nannochloropsis gaditana* meal. Assessed using the Environmental Footprint assessment 2.0. method.

Figure 14 shows the characterised environmental impacts of *Nannochloropsis* dried meal produced using the conventional nutrient medium compared to those of *Nannochloropsis* dried meal produced using nitrogen extracted from aquaculture sludge. The results are interesting and are a good example of why assessing the sustainability of a product based upon a single impact such as global warming potential (CO_2-equivelents) can encourage misleading outcomes. It is important to note that algal-meal produced using nitrogen extracted from sludge does not perform favourably to meal produced using conventional nutrient mediums across many of the impacts. Figure 15 shows a comparison between the quantity of conventional medium to deliver a functional unit of 1kg of nitrogen, and the quantity of nitrogen extracted from sludge required to deliver the equivalent functional unit. Unsurprisingly, the pattern is the same as in Figure 14 (albeit the differences between the two nutrient sources are larger), with the conventional nutrient medium have greater contributions towards terrestrial acidification, land use, and mineral resource impacts, than the alternative, which has greater impacts towards all other categories. Table 11 shows how switching from the conventional nutrient mix to the nutrient from valorised sludge alters the proportional contribution of infrastructure, energy consumption, and nutrient supply to each environmental impact category.

This should not be surprising, for various reasons. Firstly, it should not be assumed to be inherently logical that valorised wastes or byproducts, or circular economic solutions, should necessarily be associated with enhanced environmental performance. It should be born in mind that any subsequent valorisation of byproducts (etc.) will usually, if not always, involve economic interventions (further processes) that otherwise would not take place, and the associated environmental impacts such activity will bring. It is notable in this study that sludge from which nitrogen is valorised was considered to be burden free, and so no environmental impacts where attributed to it. Thus, activities associated with the provision of infrastructure and energy are the sources of contributions (e.g., Figure 10. The likely reason for the comparatively, generally poorer performance of nitrogen extracted from sludge could be the nature of the data used for compiling its life cycle inventory. The processes that featured in the iFishiENCi project and which where inventoried in this life cycle study, are based on a laboratory scale procedure. Larger scale production processes often have lower inputs and waste outputs per unit product than do smaller production processes, due to economy-of-scale. It is a reasonable assumption that a commercial scale system would be operated more efficiently in-order to achieve optimal profit, and that further reductions in environmental impacts are possible, potential tipping comparison in favour of nitrogen extracted from sludge.

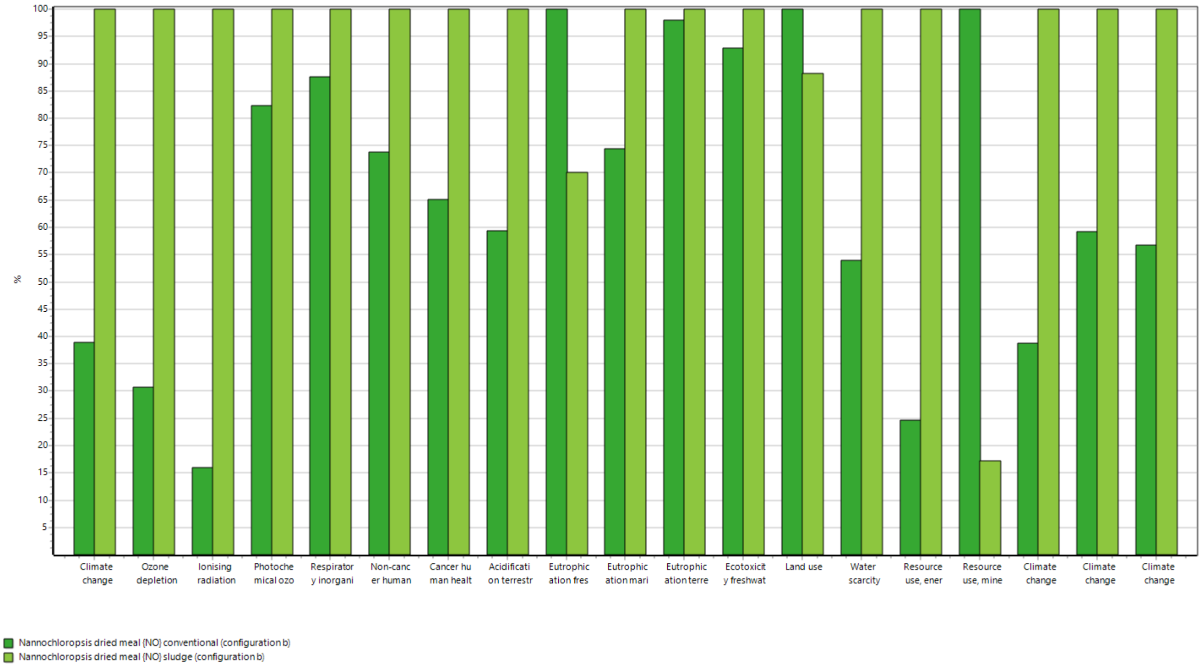


Figure 14. Characterised potential environmental impacts from the production of dried *Nannochloropsis gaditana* meal using the conventional nutrient meal, compared to those of dried *Nannochloropsis gaditana* meal produced using nitrogen extracted from sludge. Assessed using the Environmental Footprint assessment 2.0. method.

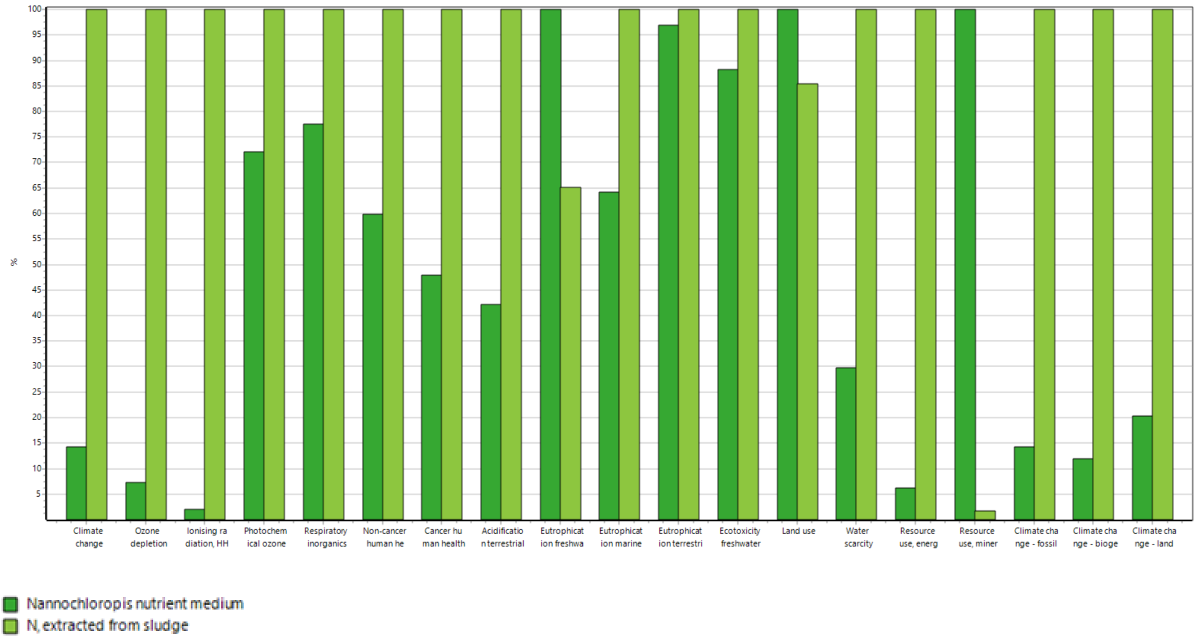


Figure 15. Comparison between the characterised environmental impacts from producing the quantity of conventional medium to deliver a functional unit of 1 kg of nitrogen, and the impacts from producing the quantity of nitrogen extracted from sludge required to deliver the equivalent functional unit. Assessed using the Environmental Footprint assessment 2.0. method.

Table 11. The percentage difference in the proportional contribution of infrastructure, energy consumption, and nutrient supply to each environmental impact category when the conventional nutrient mix is replaced by nutrients from valorised sludge (in a quantity that supplies an equivalent amount of nitrogen). Assessed using the Environmental Footprint assessment 2.0. method.

Impact category	Unit	Infrastructure %			Energy %		
		Nanno conventional nutrients	Nanno valorised nutrients	Difference %	Nanno conventional nutrients	Nanno valorised nutrients	Difference %
Climate change	**kg CO2 eq**	45.801	48.513	+2.711	28.084	29.746	+1.662
Ozone depletion	**kg CFC11 eq**	56.211	51.548	-4.664	25.862	23.716	-2.146
Ionising radiation, HH	**kBq U-235 eq**	22.378	16.031	-6.347	66.768	47.832	-18.936
Photochemical ozone formation, HH	**kg NMVOC eq**	32.375	59.638	+27.263	12.095	22.279	+10.185
Respiratory inorganics	**disease inc.**	34.643	57.748	+23.105	16.618	27.700	+11.083
Non-cancer human health effects	**CTUh**	31.798	54.990	+23.192	15.201	26.288	+11.087
Cancer human health effects	**CTUh**	22.595	36.551	+13.956	27.900	45.132	+17.232
Acidification terrestrial and freshwater	**mol H+ eq**	36.520	56.891	+20.371	13.798	21.494	+7.697
Eutrophication freshwater	**kg P eq**	11.227	55.333	+44.107	3.022	14.895	+11.873
Eutrophication marine	**kg N eq**	28.685	57.408	+28.723	10.135	20.283	+10.148
Eutrophication terrestrial	**mol N eq**	26.184	59.492	+33.308	9.518	21.625	+12.107
Ecotoxicity freshwater	**CTUe**	32.616	62.928	+30.313	10.469	20.199	+9.730
Land use	**Pt**	10.154	38.808	+28.654	8.875	33.920	+25.045
Water scarcity	**m3 depriv.**	15.736	20.612	+4.876	48.298	63.264	+14.966
Resource use, energy carriers	**MJ**	46.045	40.702	-5.343	33.669	29.762	-3.907
Resource use, mineral and metals	**kg Sb eq**	14.976	86.711	+71.736	0.816	4.723	+3.908
Climate change - fossil	**kg CO2 eq**	46.077	48.830	+2.753	27.614	29.264	+1.650
Climate change - biogenic	**kg CO2 eq**	23.787	23.840	+0.053	66.829	66.979	+0.150
Climate change - land use and transform	**kg CO2 eq**	28.897	31.503	+2.606	51.616	56.271	+4.655

Figure 16 shows a comparison between the production of standard catfish feed (section), catfish feed containing *N. gaditana produced* using a conventional nutrient mix, and the production of feed containing *N. gaditana* grown using N extracted from sludge. To all categories except climate change associated with land use and transformation, production of feed containing algae, regardless of the type of nutrient medium, has the greatest contributions. The diet containing algae produced using nitrogen extracted from sludge has greater contributions towards 15 of the 19 categories than does algae produced using a conventional nutrient mix. Its contributions are more than 50% higher than the conventionally produced algae towards four of these (ozone depletion, ionising radiation, energy resource use, and fossil fuel induced climate change). Conversely, the standard diet has greater contributions towards freshwater eutrophication and land use, and dramatically greater contributions towards mineral and metal resource use. Somewhat unsurprisingly, the pattern of the differences between each diet is similar (although not in magnitude) to that shown in Figure 14 and Figure 15. However, it is interesting that such a small inclusion rate of algae (5%) is associated with a relatively large increase in potential emissions towards some impact categories. As can be seen from Figure 17, the *N. gaditana* meal is a major contributor, outweighing the contributions of all other ingredients combined towards many of the categories. To some, this may seem a startling result, especially considering that algae based aquafeeds have been championed through various channels as being an environmentally sustainable alternative to more conventional formulas. Initiatives to produce microalgae commercially have not always been successful due to the costs of production, and microalgae can, in general, be considered a high value product. This is largely due to the energy use required to supply photosynthesis (especially in temporal regions of lower natural irradiance) and the biological limitations to biomass productivity. The latter comment implies one possible remediator: genetic engineering. Without contemplating the relevant legislative bottlenecks or perceived environmental issues of such an approach, it may be possible to enhance the productivity of microalgae in proportion to the supply of nutrients and photosynthetically available irradiation. A reduction in impacts from microalgae production may also be achieved through economy of scale. In this study an inventory was created for a 1ha production system. Indeed, a techno-economic analysis performed by Vàzquez-Romero et al. (2022) found that the cost of production was reduced by 51.26% by increasing the scale from 1ha to 10ha, and by 59.36% by increasing from 1 ha to 100 ha. Reduced costs through a reduction in inputs per unit product implies a reduction in environmental impacts.

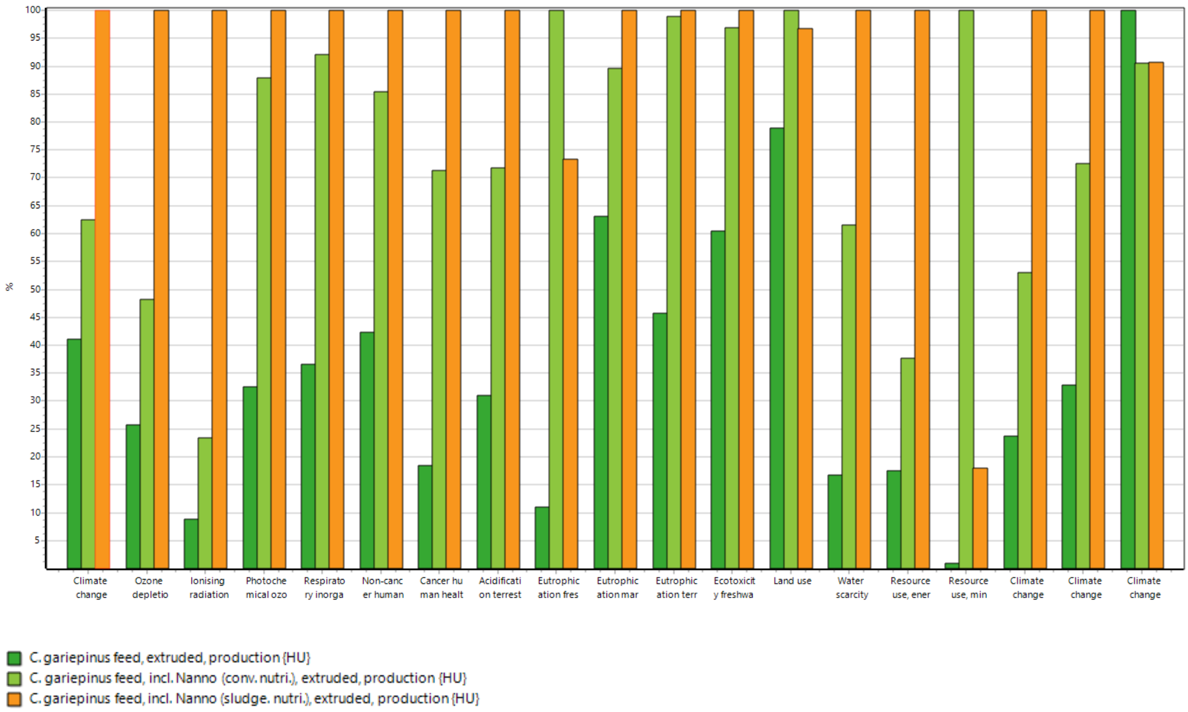


Figure 16. Comparison between the characterised environmental impacts from *the production of standard catfish feed and the production of catfish feed containing N. gaditana* using a conventional nutrient mix, and the production of feed containing *N. gaditana* grown using nitrogen extracted from sludge. Assessed using the Environmental Footprint assessment 2.0. method.

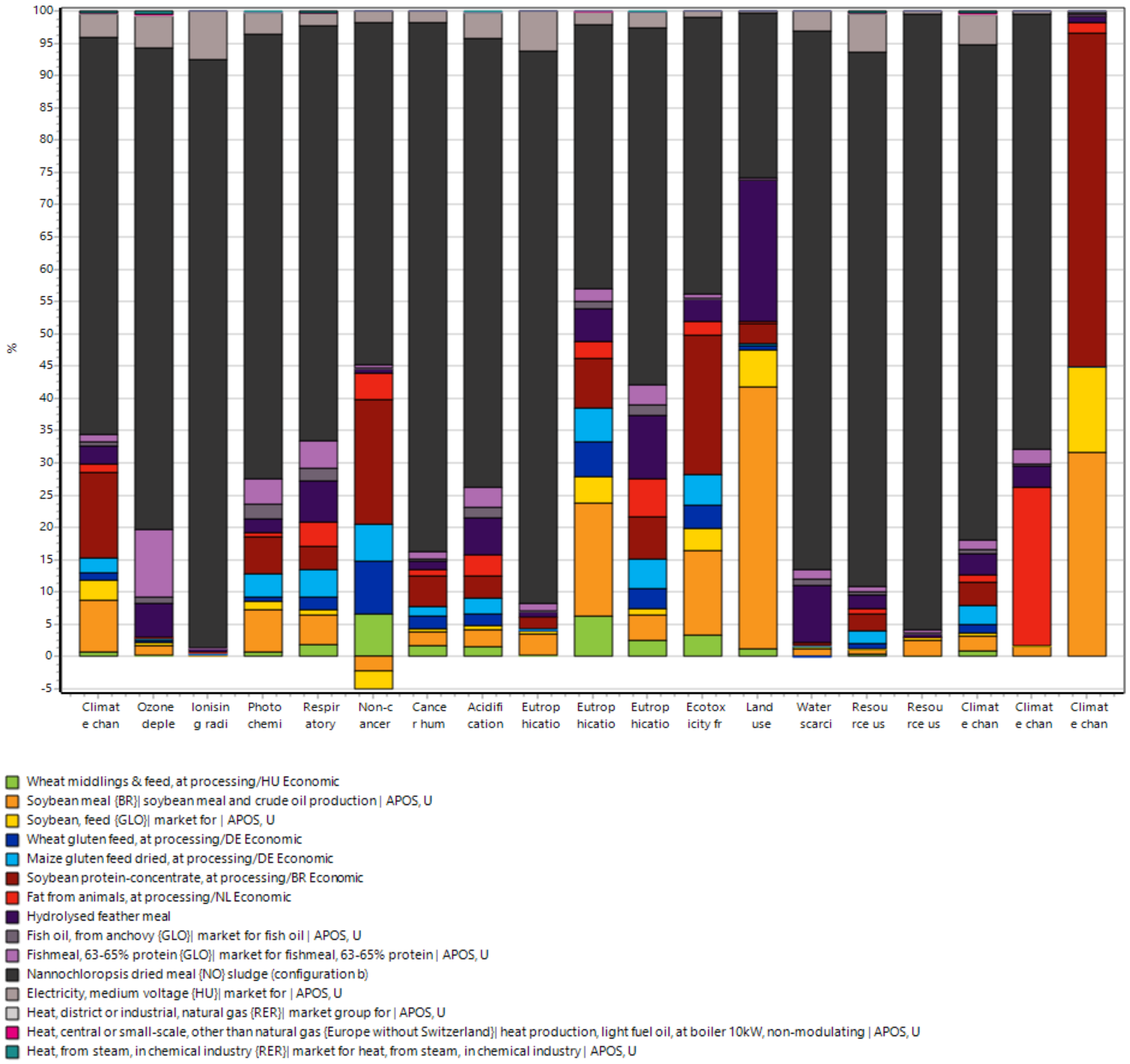


Figure 17. Characterised potential environmental impacts from the production of catfish with dried *Nannochloropsis gaditana* meal (produced nitrogen extracted from sludge) included as an ingredient at the rate of 5%. Assessed using the Environmental Footprint assessment 2.0. method.

Table 12. The characterised impact potential values of the standard diet with diet A (including algal meal produced using the conventional nutrient mix) and diet A (including algal meal produced using the nitrogen extracted from sludge).

Impact category	Unit	Standard diet	Diet A		Diet B	
		Indicator value	Indicator value	Difference	Indicator value	Difference
Climate change	kg CO2 eq	2.529	3.844	+1.316	6.149	+2.305
Ozone depletion	kg CFC11 eq	0.000	0.000	+0.000	0.000	+0.000
Ionising radiation, HH	kBq U-235 eq	0.207	0.545	+0.338	2.331	+1.786
Photochemical ozone formation, HH	kg NMVOC eq	0.005	0.014	+0.009	0.015	+0.002
Respiratory inorganics	disease inc.	0.000	0.000	+0.000	0.000	+0.000
Non-cancer human health effects	CTUh	0.000	0.000	+0.000	0.000	+0.000

Cancer human health effects	CTUh	0.000	0.000	+0.000	0.000	+0.000
Acidification terrestrial and freshwater	mol H+ eq	0.010	0.022	+0.013	0.031	+0.009
Eutrophication freshwater	kg P eq	0.001	0.007	+0.006	0.005	-0.002
Eutrophication marine	kg N eq	0.007	0.010	+0.003	0.011	+0.001
Eutrophication terrestrial	mol N eq	0.034	0.074	+0.040	0.075	+0.001
Ecotoxicity freshwater	CTUe	6.957	11.159	+4.203	11.512	+0.353
Land use	Pt	1458.415	1847.040	+388.625	1786.035	-61.005
Water scarcity	m3 depriv.	0.349	1.278	+0.929	2.075	+0.797
Resource use, energy carriers	MJ	16.281	35.076	+18.795	92.920	+57.844
Resource use, mineral and metals	kg Sb eq	0.000	0.001	+0.001	0.000	-0.001
Climate change - fossil	kg CO2 eq	1.162	2.591	+1.429	4.882	+2.291
Climate change - biogenic	kg CO2 eq	0.013	0.028	+0.015	0.038	+0.011
Climate change - land use and transform.	kg CO2 eq	1.354	1.226	-0.129	1.228	+0.003

To account for possible improvements through economies of scale, the inputs to the nitrogen extraction from sludge product stage, and the *N. gaditana* dried meal production stage, have been reduced by 50% (although the input quantity of nutrient mix, or of nitrogen from sludge to algae production was not altered). Following this change, a new comparison can be made between the standard diet, diet A, and diet B, as shown in Figure 18. Before the inputs to nutrient extraction from sludge and to *N. gaditana* production where reduce, diet B had greater contributions than diet A towards most of the impacts (Figure 18). Now the inputs have been reduced by 50%, diet B now has lower contributions that diet A towards 11 of the 19 categories, and for 9 of these categories the contributions from diet B are more than 5% lower. The contributions of diet B towards freshwater eutrophication are 55% lower than diet A, and towards mineral and metal resource use they are 89.2% lower. **These results show that replacing conventional nutrient mixes with nitrogen from valorised sludge may potentially reduce many of the environmental impacts associated with the cultivation of dried *N. gaditana* meal, and of feeds containing this product as an ingredient**. However, it is important to note that the standard diet still performs better than diet A and diet B in 18 of the 19 impact categories. The standard diet has the most contributions towards climate change from land use and transformation, because it has a greater inclusion rate of terrestrial arable crops than does diet A or diet B.

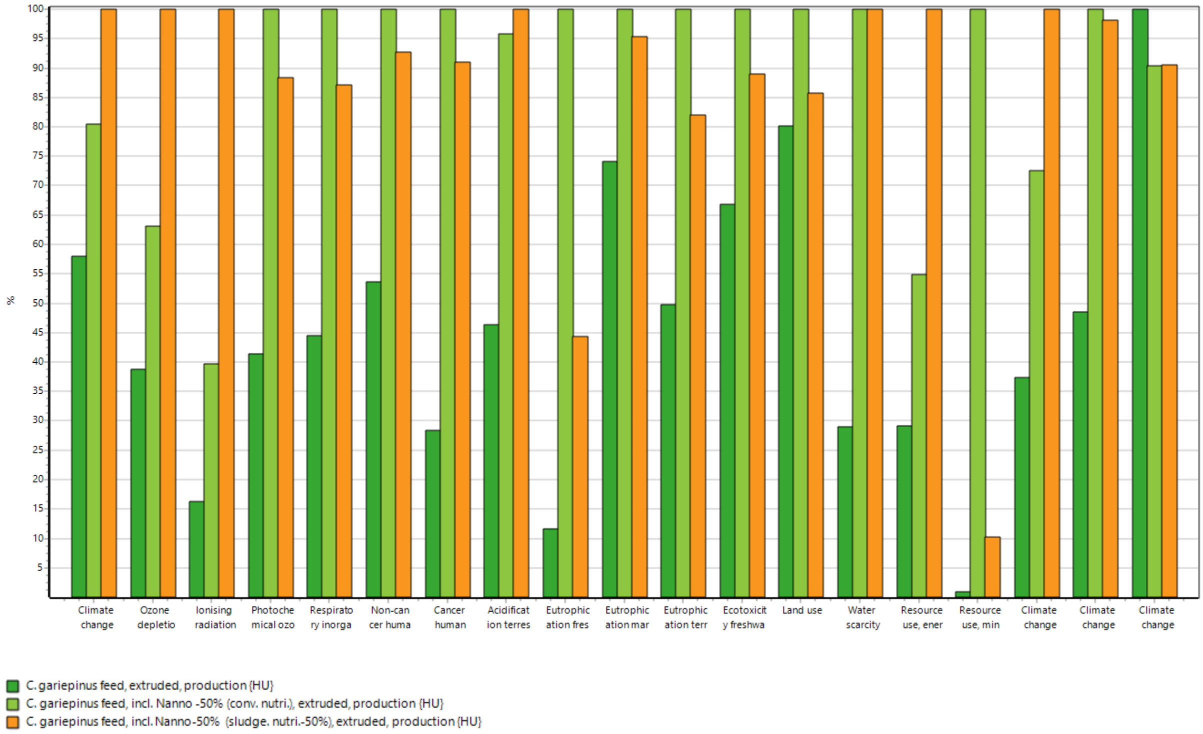


Figure 18. A comparison of the environmental impacts from the standard diet, diet A, and diet B, when the inputs to the nitrogen extraction from the sludge product stage, and the *N. gaditana* dried meal production stage, have been reduced by 50 %. Assessed using the Environmental Footprint assessment 2.0. method.

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7 Annex

Table 13. Impact categories, category indicators (and units), and the respective impact assessment models that comprise of the EU Environmental Footprint method version 2.0.

Impact category	Indicator	Unit	LCIA method
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO2 eq	Baseline model of 100 years based on IPCC
Ozone depletion	Ozone Depletion Potential	kg CFC-11eq	Steady-state ODPs
Human toxicity, cancer effects	Comparative Toxic Unit for humans	CTUh	USEtox 2.1. model
Particulate matter / Respiratory inorganics	Human health effects associated with exposure to PM2.5	Disease incidences	PM method recommended by UNEP
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235	Human health effect model
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS
Acidification	Accumulated Exceedance	mol H+ eq	Accumulated Exceedance
Eutrophication, terrestrial	Accumulated Exceedance	mol N eq	Accumulated Exceedance
Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model
Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox 2.1.
Land use	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment)	Dimensionless, aggregated index of kg biotic production / (m^2 *a) kg soil / (m^2 *a) m3g. water / (m^2*a)	Soil quality index based on LANCA
Water use	User deprivation potential (deprivation weighted water consumption)	kg world eq. deprived	Available WAter REmaining (AWARE)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML method
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML method